TA1 - 11:00

SIMULATION OF TIME-CONTROL PROCEDURES FOR TERMINAL AREA FLOW MANAGEMENT

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ABSTRACT

Simulations of a terminal area traffic-
management system incorporating automated schedul-
ing and time-control (four-dimensional (4D)) tech-
niques conducted at NASA Ames Research Center
jointly with the Federal Aviation Administration,
have shown that efficient procedures can be devel-
oped for handling a mix of 4D-equipped and conven-
tionally equipped aircraft. A crucial role in
this system is played by an ATC host computer
algorithm, referred to as a speed advisory, that
allows controllers to maintain accurate time
schedules of the conventionally equipped aircraft
in the traffic mix. Results are of the most
recent simulations in which two important special
cases were investigated. First, the effects of a
speed advisory on touchdown time scheduling are
examined, when unequipped aircraft are constrained
to follow fuel-optimized profiles in the near-
terminal area, and rescheduling procedures are
developed to handle missed approaches of
4D-equipped aircraft. Various performance
measures, including controller opinion, are used
to evaluate the effectiveness of the procedures.

INTRODUCTION

A proposed element of a future air traffic
control (ATC) system is an on-board guidance sys-
tem that can predict and control the touchdown
time of an aircraft to an accuracy of a few sec-
onds throughout the descent. The performance and
feasibility of these systems, also known as four-
dimensional (4D) guidance systems, have been dem-
onstrated in several flight test programs (1,2).

In applying 4D guidance, the main problem is
the development of ATC procedures that can exploit
the on-board time-control capability. An early
study of this problem developed terminal area
procedures under the assumption that all aircraft
are 4D-equipped (3). However, before reaching the
goal of a future system in which all aircraft are
4D-equipped, it is necessary to study problems in
the long transition period, in which the traffic
is composed of a mix of conventionally equipped
and 4D-equipped aircraft. The basic difficulty is
that in the 4D mode aircraft are separated by
time, whereas in the conventional mode they are
separated by distance. Developing techniques to
handle both types of aircraft effectively is a
complicated task that has been the subject of a

series of real-time simulation studies at NASA
Ames Research Center.

In 1982 a real-time simulation study inves-
tigated the operational problems of mixing
4D-equipped and -unequipped aircraft in the
terminal area (4). In that initial study, all
4D-equipped or -unequipped aircraft departed the
top-of-descent feeder fix exactly at their
assigned departure times. The 4D-equipped air-
craft then flew their descents to touchdown with-
out controller intervention. Unequipped aircraft
flew profile descents to a point 30 n. mi. from
touchdown, where they were radar-vectored onto a
standard instrument landing system (ILS) approach.
The study concluded that ATC procedures could be
developed to handle efficiently even low percent-
ages of 4D-equipped aircraft in the traffic mix.
Moreover, the fuel efficiency of unequipped air-
craft was not reduced by the special controller
procedures adopted to accommodate 4D-equipped
aircraft.

The objective of this paper is to describe
recent follow-on simulations of procedures for
handling more difficult traffic problems than were
simulated in the baseline study of Ref. 4. Thus,
in one experiment unequipped aircraft were allowed
to depart the top-of-descent feeder fix with large
random time errors, and computer-generated adviso-
ries were used to reduce the adverse effects of
these errors. In the most recent experiments,
controllers evaluated the feasibility of vectoring
unequipped aircraft to follow a specified hori-
zontal profile in the near-terminal area.
Finally, procedures were tested to handle missed
approaches of 4D-equipped aircraft.

The paper begins with a brief review of a
method for designing a scheduling system that
assigns conflict-free landing time slots. Then
the simulation facility, controller procedures,
and test variables used in the experiment are
described. Finally, simulation results are pre-
sented by evaluating controller opinion and work-
load for the various test conditions.

The study described in this paper is part of
a program of advanced flow control research con-
ducted jointly by Ames Research Center and the
Federal Aviation Administration (FAA) Technical
Center.

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A SCHEDULING SYSTEM FOR THE MIXED ENVIRONMENT

The 4D-equipped aircraft have the capability of meeting a touchdown time assignment to an accuracy of a few seconds. To use this capability to formulate efficient operational procedures for the time scheduling of all aircraft in the terminal area, it is necessary to 1) determine the inter-arrival time separations for two consecutive aircraft to be used in aircraft scheduling; 2) develop a scheduling algorithm for assigning landing times; and 3) develop a rescheduling algorithm to fit missed approaches of 4D-equipped aircraft back into the terminal area flow.

Time Separation Requirements

The present ATC system uses radar vectors and speed control to space aircraft so that the minimum separation distance rules are not violated. The rules depend on aircraft weight category (small for lowest weight category, large for medium weight category, and heavy for largest weight category) and are summarized in Fig. 1. For example, if a small aircraft is in trail following a large aircraft in the landing sequence, these two aircraft must be separated by at least 4 n. mi. during the entire length of the common flightpath.

TRAILING AIRCRAFT

		SMALL	LARGE	HEAVY
FIRST TO LAND	SMALL	3	3	3
	LARGE	4	3	3
	HEAVY	6	5	4

Fig. 1 Minimum separation distance (n. mi.).

These minimum separation distances can be converted to minimum separation times using knowledge of the speed profile of each aircraft weight class. In this way, a matrix of minimum time separations is determined as shown in Fig. 2.

TRAILING AIRCRAFT

		SMALL	LARGE	HEAVY
FIRST TO LAND	SMALL	98	74	74
	LARGE	138	74	74
	HEAVY	167	114	94

Fig. 2 Minimum separation time (sec).

It is assumed that, if there are two consecutive 4D-equipped aircraft, the interarrival times given in Fig. 2 can be used for scheduling purposes. However, unequipped aircraft will need additional time buffers to prevent distance separation violations. The technique for obtaining these buffers is discussed in Ref. 4. For the purposes of this study, it was assumed that if one of the two consecutive aircraft was unequipped, a buffer of 10 sec was added to the separation time; if both aircraft were unequipped, a buffer of 20 sec was added.

Scheduling Algorithm

Based on knowledge of the feeder fix departure time and on the desired time to traverse the route, a desired touchdown time for each aircraft can be determined. Using a first-come, first-served ordering protocol at touchdown and the time-separation matrix developed in the previous section, the time schedule at touchdown is obtained. It is possible to increase the capacity by altering the first-come, first-served order; thus, future studies will incorporate more efficient ordering algorithms to take advantage of bunching of weight and speed classes (5).

In addition to setting up an initial schedule, algorithms are required to revise the schedule. For example, as shown later, missed approaches need to be accommodated. The controller may need to change the aircraft arrival rate, block out specific time periods from the computer schedule to accommodate a missed approach or an emergency landing, or require a few aircraft to be scheduled in a specified order. This can be accomplished by manipulating the existing schedule. Two procedures used during these simulations to manipulate the existing schedule were the halt command and the capture probe (CP) inquiry. (The CP inquiry will be discussed in a later section.)

To explain the halt procedure, let us suppose that an initial schedule has been established for those aircraft that have departed the feeder fix (denoted active aricraft) and those which have not yet departed the feeder fix (denoted inactive aircraft). Controllers may need to hold the inactive aircraft for a time t_h to accommodate a missed approach. A rescheduling algorithm leaves the time assignments for the active aircraft unaltered, but revises the touchdown times of inactive aircraft by at least t_h. An illustration of this is found in Fig. 3. For example, inactive aircraft (aircraft that have not yet departed the feeder fix) E1 and G1 are halted while A1 executes a missed approach. Aircraft are assumed to be scheduled 2 min apart. When A1 is rescheduled into the traffic flow, it is assigned to 9:14 since there is an open slot at that time. With the 2-min halt, E1 would be rescheduled for 9:16, but since there is a previously scheduled active aircraft landing at 9:16, E1 will be rescheduled for 9:18 and G1 for 9:20. The effect of the missed approach is to leave active aircraft as previously scheduled, but to revise the inactive aircraft schedule by 2-4 min.

TEST PROCEDURE

Simulation Facility

The simulations were conducted using the Ames ATC Simulation Facility. It includes two air traffic controller positions, each having its own

INITIAL SCHEDULE (* = ACTIVE AIRCRAFT)		EVENT:	REVISED SCHEDULED (* = ACTIVE AIRCRAFT)	
AIRCRAFT ID	SCHEDULED TOUCHDOWN TIME (HRS : MIN)	A1 EXECUTES A MISSED APPROACH.	AIRCRAFT ID	SCHEDULED TOUCHDOWN TIME (HRS : MIN)
A1*	9:06	CONTROLLER ISSUES	B1*	9:08
B1*	9:08		C1*	9:10
C1*	9:10	HALT FOR	D1*	9:12
D1*	9:12		A1*	9:14
E1	9:14	$T_h = 2$ MIN	F1*	9:16
F1*	9:16		E1	9:18
G1	9:18		G1	9:20

Fig. 3 Sample scheduling revision.

color computer graphics display; one was designated arrival control and the other, final control. In proximity to the color displays, there was a keyboard with which the ATC-display-related requests were entered into the controller displays and the simulation computer. Such inputs included changing the position of an aircraft identification tag, transferring an aircraft between control sectors, or stopping and restarting the flow of traffic at the feeder fixes.

Each keyboard pilot position was able to control up to 10 omputer-generated aircraft simultaneously. The clearance vocabulary included standard heading, speed, and altitude clearances as well as special clearances for 4D-equipped aircraft. In this study, three keyboard pilot positions were used; one was responsible for all aircraft in the arrival sector while the other two divided responsibility for aircraft in the final sector. Previous studies have used one or two piloted simulators connected by voice and data link to the ATC Simulation Facility. However, in this study, no piloted simulator was used. It is planned to include an airline-quality simulator as well as a helicopter simulator in future studies of the mixed environment.

Scenario and Controller Procedures

The simulated terminal area is based on the John F. Kennedy (JFK) International Airport in New York. The route structure and runway configuration investigated as seen by the controllers are shown in Fig. 4. It is assumed that instrument flight rule conditions prevail and that all aircraft use runway 4R; furthermore, no departure flights, winds, or navigation errors are simulated. Two routes, Ellis from the north and Sates from the south, are high-altitude routes flown by large or heavy jet-transport aircraft. Both 4D-equipped and -unequipped aircraft on these routes fly profile-descent, fuel-conservative

procedures, providing a mix of the same speed class on the same route. Low-performance aircraft flew the Deerpark route from the east, but used the same final approach and landed on the same runway as the jet traffic. The Deerpark traffic was unequipped and always constituted 25% of the traffic mix.

During this study, an extended terminal area was used. Aircraft entered the extended terminal area at the feeder fix points and were at cruise speed and altitude. The total distance to be flown along each of the jet routes was 120 n. mi. and that flown by low-performance aircraft was 60 n. mi. Two air traffic controller positions were established, arrival control and final control. The arrival controller controlled aircraft from all three feeder fixes and transferred traffic to the final controller at approximately 30 n. mi. from touchdown.

Control procedures differed for 4D-equipped and -unequipped aircraft. Controllers were instructed to monitor the progress of 4D-equipped aircraft after the time assignment had been established, and to override the ground-computer scheduling system only if necessary to ensure safe separation. Any 4D-equipped aircraft could also be controlled by conventional methods and treated as unequipped. Alternatively, a 4D-equipped aircraft which had been taken off the 4D route could be given a waypoint to recapture a 4D route, and be given a revised landing time. Unequipped aircraft were considered to be navigating in the conventional manner via very-high-frequency omnidirectional range procedures, with altitude clearances, radar vectors, and speed control.

Flight Data Table

To assist the controller in integrating the 4D-equipped and -unequipped traffic, a flight data table (FDT) was provided on each controller
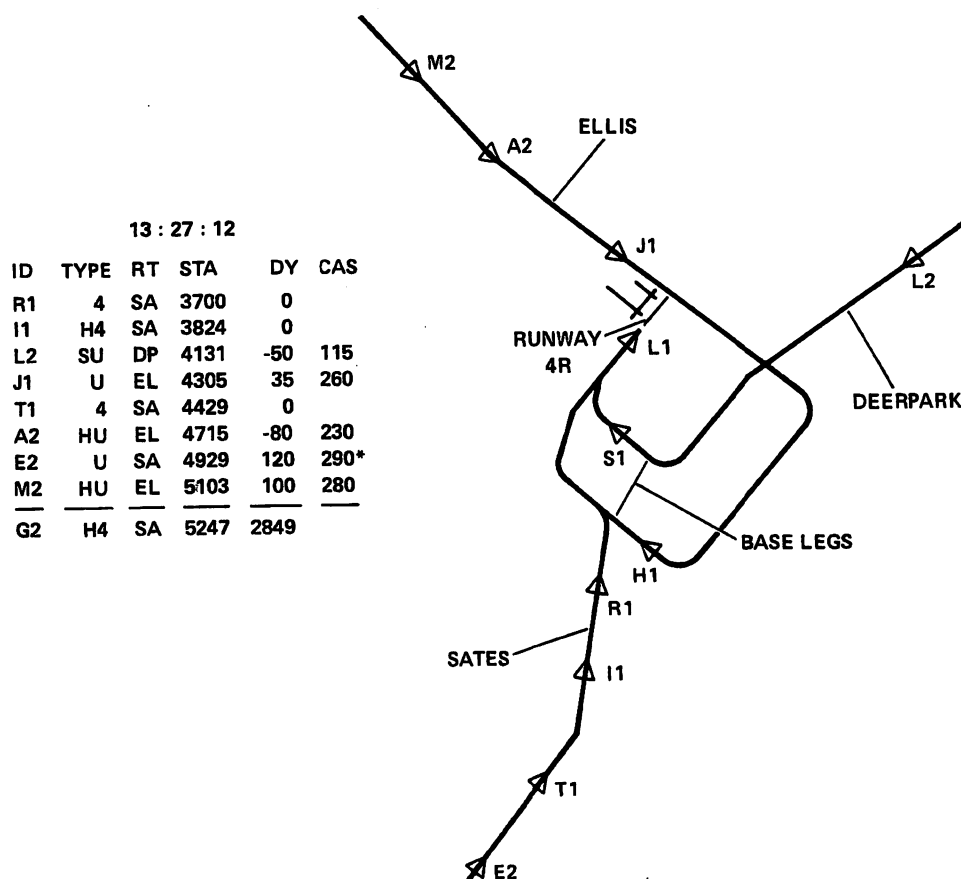
13 : 27 : 12

ID	TYPE	RT	STA	DY	CAS
R1	4	SA	3700	0	
I1	H4	SA	3824	0	
L2	SU	DP	4131	-50	115
J1	U	EL	4305	35	260
T1	4	SA	4429	0	
A2	HU	EL	4715	-80	230
E2	U	SA	4929	120	290*
M2	HU	EL	5103	100	280
G2	H4	SA	5247	2849	

Fig. 4 Controller display showing route structure and flight data table.

display. A typical arrival controller display is shown in Fig. 4. The map portion of the display provides a horizontal display of traffic in the terminal area. Each aircraft position is shown by a triangular symbol, and the block of data next to each aircraft provides the aircraft identification, type, altitude, and speed. The flight data table in the upper left portion of the display provides schedule information for all aircraft in the approach control sector. At the top of the table, the time is shown in hours, minutes, and seconds. The first column shows the aircraft identification (ACID), such as "R1." The second column provides aircraft type (TYPE) which includes a) weight category (small (S), large (blank), or heavy (H)); and b) 4D status (equipped (4) or unequipped (U)). The third column provides the assigned route (RT). Also shown is the scheduled time of arrival (STA) at the runway in minutes and seconds. Thus, R1 is scheduled to touch down at 13:37:00. Note that touchdown times are shown for all aircraft, whether 4D-equipped or -unequipped. For the 4D-equipped aircraft, this is the time assigned by the ground-based computer system to touchdown. For the unequipped aircraft, no time assignment is given to the aircraft; rather, the controller is to use this information, the positions of the 4D-equipped aircraft as they traverse their routes, and the speed advisories to generate appropriate vectors to the unequipped aircraft so that they touch down at the time indicated. The next column is the expected delay (DY), where the expected delay at touchdown is in seconds. In an effort to simulate an environment in which an advanced en-route metering system is not present, the unequipped aircraft were assumed to depart with an initial time error uniformly distributed in the range ±120 sec.* Thus, if an aircraft departed the feeder fix 90 sec late, a DY of 90 would be displayed, indicating that unless controller action was taken, the aircraft would touch down 90 sec late. Early arrivals were indicated by a negative value in the DY column; late arrivals by a positive value. All 4D-equipped aircraft departed the feeder fix at the scheduled

*These delays are considered large, since, for example, two consecutive 4D-equipped aircraft could arrive in the final control sector in reversed order if there are consecutive departure errors of +60 sec and -60 sec. Also, some informal testing of controllers by the FAA in the segment area indicated that, with practice, controllers could get aircraft over a designated arrival fix within ±1 min of an assigned time, without any computer-generated assists.

departure time. In flight tests, it has been shown that 4D-equipped aircraft can meet time schedules within ±5 sec; hence, these small errors were neglected (1,2).

Finally, aircraft below the dotted line in Fig. 6 are aircraft which will depart the feeder fix within the next 5 min (shown in the right-most column) indicated by the feeder fix-departure time in minutes and seconds.

Speed Advisory System

In the scheduling process all aircraft, 4D-equipped or -unequipped, are assigned a touchdown time. For the 4D-equipped aircraft, this time assignment generated on the ground is transmitted to the aircraft, which uses its on-board 4D system to land at the assigned time. However, unequipped aircraft must be controlled by vectors and speed clearances. It is the task of the controller to issue these clearances so as to meet the assigned time. However, in the arrival sector, 120 n. mi. from touchdown, the controller cannot predict with accuracy when an aircraft will land and how it will fit into the landing sequence.

Thus, an algorithm known as a speed advisory system was developed to give the arrival controller a tool for controlling the landing time of unequipped aircraft. With inputs of current position, altitude, and speed, the speed advisory system computes and displays to the controller the calibrated airspeed (CAS) that is required to make the aircraft land at the desired landing time (6).

The arrival controller, presented with a table of speed advisories for the unequipped aircraft on his or her display, is responsible for issuing the advisories to pilots starting their descents. During the descent the speed advisory system updates the time error by comparing the predicted position with the actual position of the aircraft. If the error exceeds ±20 sec, the speed advisory is updated on the controller's display. This feature helps to reduce time errors caused by unknown winds and pilot tracking inaccuracies.

Once the CAS advisory is issued and the pilot adjusts the speed accordingly, the gap between the reference position and the actual aircraft position narrows and the magnitude of the delay is reduced. If the magnitude of the delay is less than 20 sec, or the aircraft is less than 25 n. mi. from touchdown, the CAS advisory is removed. This discourages the inappropriate use of the advisory. In the final control sector, the controller uses conventional vectoring techniques to correct any remaining spacing errors.

Capture Probe

Another controller assist that was provided to handle missed approaches was a CP inquiry which assisted in determining a feasible revised touchdown time for the missed-approach aircraft. The approach controller provided the ID of the missed-approach aircraft and a specific waypoint along a route to the ground-based computer system. The computer then generated a 4D trajectory which would take the missed-approach aircraft from its present course (away from the runway) to a waypoint on a landing route and then schedule it for a second approach. On the approach controller's display, the scheduled time of arrival for that aircraft (if it were to change its course and capture that waypoint) appeared in the FDT in the appropriate time order. The time and position sequence in the FDT would be updated every 10 sec as the aircraft proceeded along its present course. When the revised scheduled time of arrival was not in conflict with the scheduled time for other aircraft, the approach controller issued a command to the pseudopilot of that aircraft to capture that waypoint. At this time, the aircraft made the change and proceeded to follow its 4D route from that waypoint, without controller assistance.

Test Conditions

In all test cases, unequipped aircraft departed the feeder fix with random departure errors uniformly distributed in the range ±120 sec. The traffic mixes examined were 0%, 25%, and 50% 4D-equipped aircraft. In all cases, the time information (STA) was displayed. Some runs displayed the CAS speed advisory and DY and some did not. In addition, simulation runs were conducted for the 0% case when STA, DY, and CAS were not displayed, which corresponds to present operations.

In a series of runs, controllers were instructed to keep unequipped aircraft on fuel-optimized profiles for cases in which 25% and 50% of the traffic was 4D-equipped aircraft. Cases distinguished between runs in which the CAS speed advisory was displayed to the controller and those in which it was not.

Another series of runs involved rescheduling missed approaches of 4D-equipped aircraft for both 25% and 50% 4D-equipped aircraft mixes. In these runs, all information contained in the FDT was displayed. In all runs the aircraft arrival rate into the terminal area was chosen so that a full schedule with no gaps was generated.

No departure traffic was simulated, and winds or navigation errors were not modeled explicitly. The tracking inaccuracies caused by navigation errors and wind uncertainties were assumed to be incorporated in the feeder fix departure errors.

Forty-eight data runs were made, each approximately 80 min long. Three air traffic controllers from the FAA Technical Center, Atlantic City, N.J., participated as subjects in these studies.

RESULTS AND DISCUSSION

Controller Evaluations of Mix Conditions and CAS Advisory

The mix conditions and the CAS advisory were evaluated in a simulation experiment conducted a year before this experiment investigating following exact routes and missed-approach procedures. Results from the earlier experiment, which were reported previously in Ref. 7, are briefly reviewed here because of their close relationship to those of the most recent experiment.

The 25% 4D-equipped case was rated by controllers as the condition with the heaviest workload. The main difficulty seemed to be that the controllers were establishing distance spacing for the majority of the traffic, and they felt that by not altering the flightpath of the 4D-equipped aircraft, they were occasionally losing some slot time. However, they were pleased with the 50% 4D-equipped case, which allowed for easy control of the unequipped aircraft. One controller commented that it was the best ratio; he could "work without being overtaxed." In this mode, fewer communications were required, the traffic flow was more orderly, and it was easy to fill the gaps between the 4D-equipped aircraft with the unequipped aircraft. The baseline case of 0% 4D-equipped aircraft was regarded as reasonable, but not because of a lessening of workload; rather, because it was the most familiar.

The controllers were provided with time-scheduling information in the FDT previously described. The controllers indicated that the only information they used was the time-ordered listing of aircraft from which the relstive order of traffic on the downwind leg and the traffic from Sates was determined. Using this information, and by not altering the 4D-equipped aircraft, controllers were able to radar vector the unequipped aircraft to their assigned landing slots.

Controllers were asked to evaluate the speed advisory. Controllers compared operations both with and without the speed advisory and evaluated the format and operational procedures established for the advisory. They commented that without the delay or advisory information displayed and with large feeder fix departure errors present, the system yielded traffic surges. Speed advisories resulted in less bunching of traffic and fewer "ties" in the merging area. With the advisories, the traffic seemed to blend together smoothly and require fewer vectors.

Following Exact Routes

In this set of experimental conditions, controllers were instructed to keep 4D-equipped aircraft along the nominal base leg route (Fig. 4). Controllers were asked to turn aircraft onto the base leg at the same point, and thereafter use only speed adjustments to control spacing. This procedure sought to keep unequipped aircraft on their planned profile descent paths longer to minimize fuel consumption. The procedure was also believed to be helpful for controlling time errors by reducing the variability of turning to base leg. One important question to be answered by these tests was whether controllers could change from path control to speed control as an alternative for making small spacing adjustments in the base leg region.

Controllers were initially hesitant when asked to keep unequipped aircraft on specified flightpaths, but, after an initial trial period with speed adjustments only, they said it seemed to go well. Nevertheless, their preference was to revert to path-stretching techniques because they were more accustomed to those procedures. The effect of the CAS advisory turned out to be important in the cases tested. In both the 25% and 50% 4D-equipped cases, it was judged easier to follow exact routes when CAS was provided than when CAS was not provided. The 25% 4D-equipped cases were found to be more difficult than the 50% 4D-equipped cases, in accordance with previous results. A comparison was made between the airspace used when controllers were and were not constrained to keep unequipped aircraft on specified flightpaths. Figures 5a and 5b are the envelope of composite plots of the flightpaths flown for these two cases. The procedure of following the exact routes in Fig. 5a has significantly reduced the area in the airspace envelope compared to that in Fig. 5b. Although the area has not been reduced to zero, it establishes the limit in accuracy of following a prescribed route using conventional vectoring techniques.

In summary, the use of heading vectors to guide the aircraft along a prescribed route and speed control to make fine adjustments in spacing is a workable alternative to path stretching. The technique is acceptable, though not preferred, by the final controller, provided that time errors are kept small at the hand-off point between approach controller and final controller.

Missed-Approach Procedures

The procedure used to handle missed approaches was that once a missed approach was executed, aircraft that had not yet departed the feeder fix were halted for 2 min. Since a landing slot had been lost because of the missed approach, a new one had to be created. This 2-min slot time was the amount decided upon to create a new slot for the mised-approach aircraft with the least amount of disruption to the rest of the traffic. Meanwhile, the missed approach proceeded along the missed-approach route toward waypoint 25 (Fig. 6). Once the 2 min had elapsed, the approach controller issued a CP inquiry for the missed approach to capture waypoint 19. When a suitable conflict-free time appeared in the FDT schedule, the approach controller instructed the pseudopilot of the missed-approach aircraft to capture waypoint 19. The new time appeared on the FDT in the proper sequence, and the 4D-equipped aircraft proceeded on its flightpath without controller assistance.
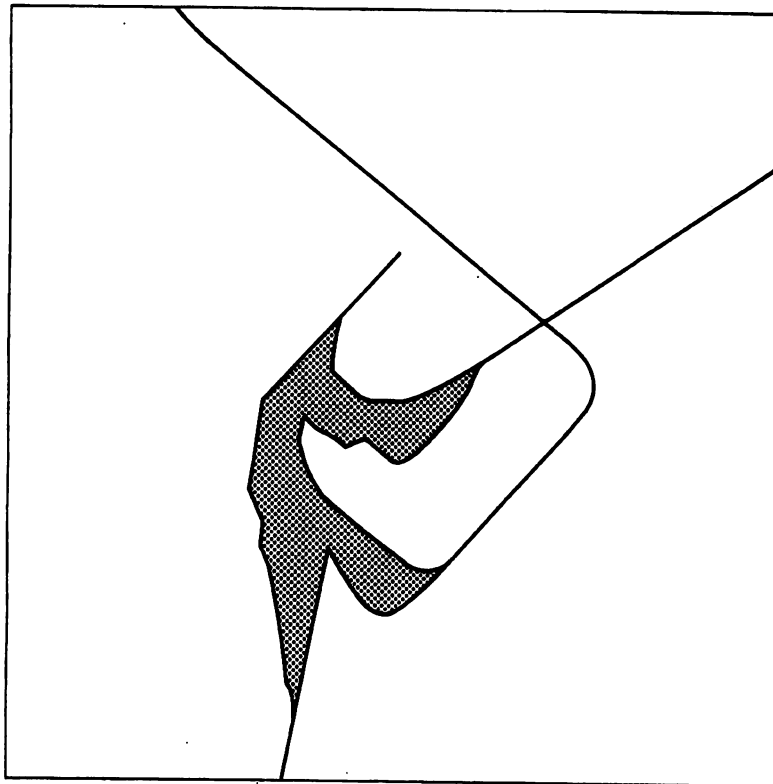
a) 50% 4D-equipped with CAS following exact routes.
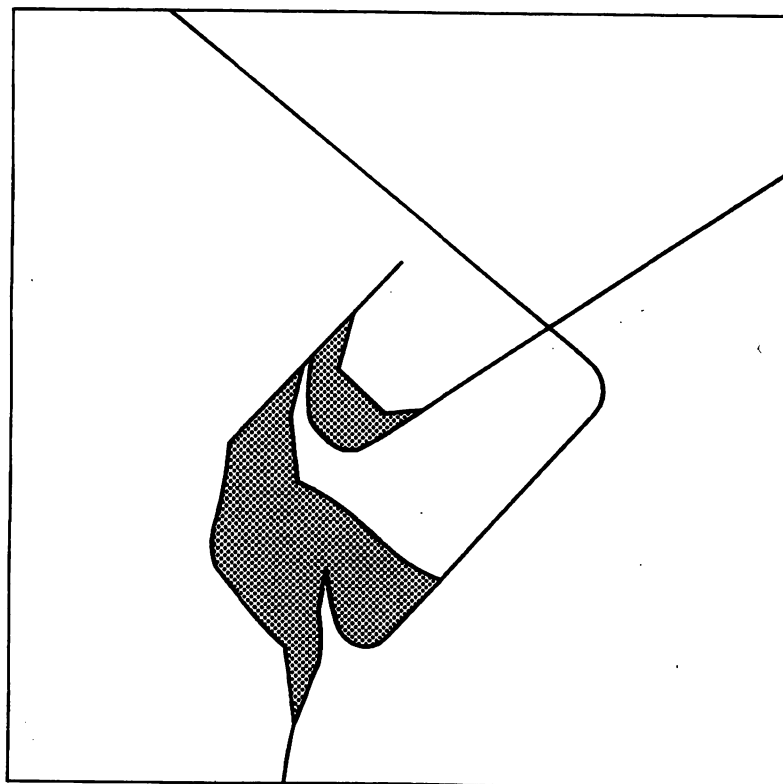
b) 50% 4D-equipped with conventional vectoring.

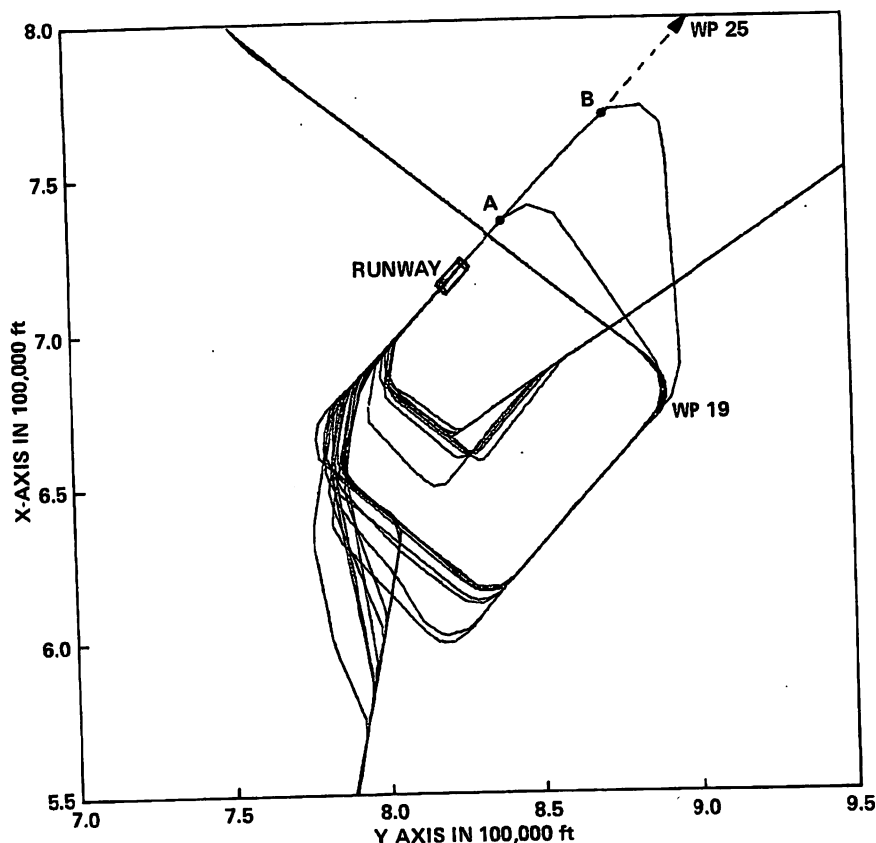Fig. 5 Composite plot of flightpaths flown.

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Fig. 6 Composite plot showing flightpaths of two missed approaches.

Controllers were generally pleased with this procedure. Controllers found that if the missed approach was rescheduled so that it was positioned behind another 4D-equipped aircraft, the controller was able to achieve the proper spacing between them. But, if the controller was forced to position the missed approach after an unequipped aircraft because of the schedule, he or she had to vector the missed approach for a longer period of time before a waypoint was captured. Workload to handle a missed approach was considered the same for both 25% and 50% 4D-equipped runs. Although only 4D-equipped aircraft executed missed approaches, they did not cause an increase in clearances to the unequipped traffic. In using this procedure, a third controller, designated the flow controller, assisted the approach controller. With the level of automation simulated here, the flow controller (who was able to view both controllers' FDTs) was invaluable in handling the logistics of rescheduling the missed approach.

Figure 6 is a typical composite plot of a 50% 4D-equipped run in which there were two missed approaches. Waypoints 19 and 25 are shown as are the routes taken by the two missed approaches. The "Capture Waypoint 19" commands were issued at points A and B in the figure. The capture trajectory generated by the on-board 4D system extends from points A and B to waypoint 19.

CONCLUDING REMARKS

A series of operational procedures for handling a mix of 4D-equipped and unequipped aircraft in the terminal area was investigated. The basic rule not to alter the 4D-equipped aircraft once they were assigned a landing time, resulted in the controllers learning to use the 4D-equipped aircraft positions to effectively vector the unequipped aircraft to their assigned landing slots.

The speed advisory algorithm proved to be an effective operational procedure for nullifying touchdown times of unequipped aircraft. This operational procedure did not create additional workload for the approach controller and allowed the final controller to handle the traffic in the same manner as if there were no initial time errors.

Handling unequipped aircraft that were constrained to follow fuel-optimized profiles in the terminal area was accomplished by using a speed advisory which helped in derandomizing the flow. Composite plots of the flightpaths flown show that control of unequipped aircraft in a 4D environment can be restricted to specified horizontal routes.

A simple rescheduling procedure was developed to handle missed approaches of 4D-equipped aircraft. This involved halting inactive aircraft

for a prespecified time to create an extra slot in the terminal flow, and then scanning a series of possible landing times for the missed approach. When a suitable touchdown time was decided upon by the approach and flow controllers, the 4D-equipped aircraft recaptured the route and no longer needed to be monitored by the air traffic controller.

Several issues raised by these simulations indicate a need for further investigation. First, a simulation should be conducted to include a piloted simulator to investigate a pilot's response to speed advisories. Second, further development of efficient ground-based 4D algorithms for unequipped aircraft is needed. And third, algorithms for optimized, revised time schedules should be developed.

REFERENCES

(1) Lee, H. Q., Neuman, F., and Hardy, G. H., "4D Area Navigation System Description and Flight Test Results," NASA TN D-7874, 1975.

(2) Knox, C. E., "Fuel Conservative Descents in a Time Based Metering Environment," Proceedings of the 18th IEEE Conference on Decision and Control, Fort Lauderdale, Fla., Dec. 1979.

(3) Tobias, L. and O'Brien, P. J., "Real Time Manned Simulation of Advanced Terminal Area Guidance Concepts for Short-Haul Operations," NASA TN D-8499, 1977.

(4) Tobias, L., "Time Scheduling a Mix of 4D Equipped and Unequipped Aircraft," NASA TM-84327, 1983.

(5) Dear, R., "Increasing Capacity with Computer-Assisted Decision Making," Proceedings of the International Air Transportation Conference, Vol. 2, May 1979.

(6) Erzberger, H. and Chapel, J. D., "Concepts and Algorithms for Terminal Area Traffic Management," Proceedings of the 1984 American Control Conference, San Diego, Calif., June 1984.

(7) Tobias, L. and O'Brien, P. J., "Simulation of Time-Control Procedures for the Advanced Air Traffic Control System," Proceedings of the 1984 American Control Conference, San Diego, Calif., June 1984.